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Appendix E

The MPD Thruster Program at JPL

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Outline

THE SEI CONTEXT

CRITICAL ISSUES OF MPD THRUSTER DESIGN

THE MPD THRUSTER PROGRAM AT JPL



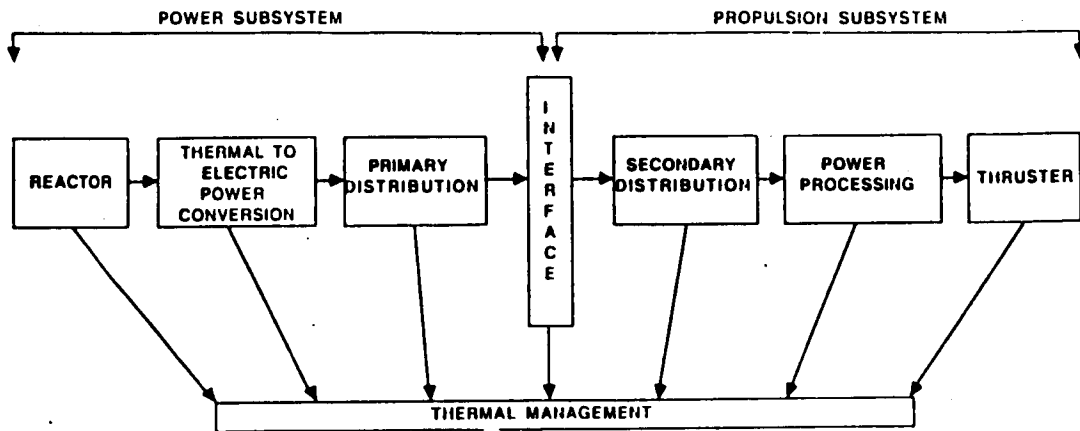
The SEI Context

- Missions:
Robotic planetary exploration (100 - 500 kWe)
Lunar and Mars Cargo (1 - 5 MWe)
Piloted Mars (5 - 40+ MWe)
- The first piloted mission is targeted for around 2015.
A round trip time of less than 1 year is desired.
- Propulsion System Options:
Chemical with aerobrake
Nuclear thermal propulsion
Nuclear electric propulsion
- NEP offers better performance than chemical or NTP for sufficiently high power (> 10 MWe) and low specific mass (< 10 kg/kWe)
- The NTP lobby, bolstered by the NERVA experience, is strong. The nuclear propulsion program has so far been arbitrarily weighted toward NTP.



The Nuclear Electric Propulsion System

- The NEP System includes:
Nuclear reactor
Power conversion
Power management and distribution
Power processing
Thruster
Thermal management
- Although electric thruster funding has been anemic for decades, funding of other essential technologies is also low or absent.



Important design considerations not shown here:
 Shielding
 Structure
 Propellant Handling
 Gimbals

Some Electric Thruster Options

- Electric thruster options include:
 - Deflagration
 - ECR
 - ICR
 - Ion
 - MPD
 - Pulsed inductive
 - Pulsed plasmoid
 - "Variable Isp"
- Ion and MPD thrusters are leaders due to their developmental heritage. The ion engine is efficient, but has a relatively low thrust density and has been developed primarily at ≤ 10 kW. The MPD thruster is simpler in design and has a higher thrust density, but has not demonstrated efficient performance with the propellants normally considered. Neither device has demonstrated the required lifetime.

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Critical Issues of MPD Thruster Development

GOAL: On a five-year time scale, demonstrate that performance required for SEI applications can be achieved or downselect to another thruster or propulsion system.

CRITICAL ISSUES: SYSTEM LEVEL

ISSUE: Definition of operational requirements

REQUIREMENT: Specification of characteristics of an MPD thruster-based propulsion system that beats the performance of competing systems for SEI missions (e.g. specific impulse, efficiency, specific mass, system power)

STATUS: Poor definition of SEI missions, requirements

APPROACH: Trade studies (including mix and match studies of MPD thruster with other sub-system options; pulsed vs. steady state operation; reliability analysis)

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Critical Issues of MPD Thruster Development (Cont'd)

ISSUE: Thruster-spacecraft interactions

REQUIREMENT: Understanding of effects on spacecraft of MPD thruster, including mechanical, thermal and electrical interfaces; dynamic effects; exhaust plume-spacecraft interactions (including contamination from propellant and erosion products); and thruster-thruster interactions

STATUS: Poor understanding of these topics

APPROACH: Analysis and design studies; supporting experimental verification. A flight demonstration is essential.

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**Critical Issues of
MPD Thruster Development (Cont'd)**

ISSUE: Operating power level

REQUIREMENT: Megawatts per thruster

**STATUS: Up to 300 kW (US); up to 800 kW (GE);
MW level (claimed by USSR) in steady state. Multi-MW
achieved in millisecond pulses.**

**APPROACH: Facilities-limited issue. US has taken an
"evolutionary" approach to high power, steady state
operation (versus an Edisonian approach).**

ISSUE: Specific impulse

REQUIREMENT: 3000 to 8000 s, depending on mission

**STATUS: Required range achieved for low (<100 kW) power
steady state and MW-level pulsed operation**

**APPROACH: Maintain desired range while increasing power,
efficiency and lifetime. Focus on electrode geometry and
propellant selection, injection.**

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**Critical Issues of
MPD Thruster Development (Cont'd)**

CRITICAL ISSUES: COMPONENT LEVEL

ISSUE: Efficiency (Electric input to directed kinetic)

REQUIREMENT: > 50%

**STATUS: 40% on H₂; nearly 70% on Li reported at
about 5000 s. (These data for pulsed or low power devices.)**

**APPROACH: Analyses and experiments focused on
the design parameters electrode geometry; magnetic
field strength and geometry (self or applied); propellant
(substance, flow rate, injection geometry); total power
level; and physical scale**

ISSUE: Lifetime

**REQUIREMENT: 10E9 N-s (on the order of 6 months,
100 N)**

**STATUS: 10E6 N-s demonstrated steady-state (500 hr,
33 kW)**

**APPROACH: Analyses and experiments focused on the
parameters total power; component operating temperature
and materials; electrode geometry and current density;
magnetic field strength and configuration; propellant**



Critical Issues of MPD Thruster Development (Cont'd)

ISSUE: Thermal management

REQUIREMENT: Remove MW of thermal power from engine at temperatures of 1400 K to 2300 K.

STATUS: Technology appears in hand; need for design and experimental verification.

APPROACH: Self-radiating grids, pumped Li loop, composite fins

ISSUE: Facility requirements

REQUIREMENT: $10E7$ l/s pumping speed (for 6 g/s Ar at $10 E-4$ torr). Must be dedicated for life tests, able to accommodate thermal load.

STATUS: Existing US facilities have pumping speeds at least an order of magnitude too small, are very expensive, and are not dedicated to MPD thruster development.

APPROACH: Establish facility requirements for various developmental tasks; use existing facilities to generate data supporting the cost of a dedicated full-up facility. Explore alternate pumping schemes. Establish pulsed-steady state correspondence.



Summary of Critical Issues

<u>ISSUE</u>	<u>A FOCUS OF JPL's MPD PROGRAM</u>
Definition of operational requirements	
Thruster-spacecraft interactions	X
Operating power level	
Specific Impulse	
Efficiency	
Lifetime	X
Thermal management	X
Facility requirements	X

JPL The MPD Thruster Program at JPL: Programmatic Overview

- **Funded under NASA RTOP**
- **FY91 Level of Effort: 3.5 WY**
- **Personnel:** T. Pivrotto (RTOP Manager)
K. Goodfellow
J. Polk
W. Thogmartin
- **Facility:** 3000 square feet
Five test chambers
Three 60 kW welding power supplies

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The MPD Thruster Program at JPL

EMPHASIS: Engine component lifetime and thermal management.

APPROACH: Theoretical and experimental specification of thermal loads and failure mechanisms

SPECIFIC ELEMENTS:

- Testbed MPD engine
- High-current cathode test facility
- Component thermal modelling
- Alkali metal propellant studies



Radiation-cooled MPD Thruster

GOAL: Develop a testbed engine to study thruster thermal behavior and life-limiting mechanisms.

PROGRESS:

- Stable operation demonstrated for
 - Power: 3-50 kW
 - Applied B-field: 0-1360 G
 - Propellant/Flow rate: Argon 0.07-0.43 g/s
Ammonia 0.07-0.30 g/s
- Graphite and tungsten nozzles tested
- Two cathode geometries tested



Radiation-cooled MPD Thruster

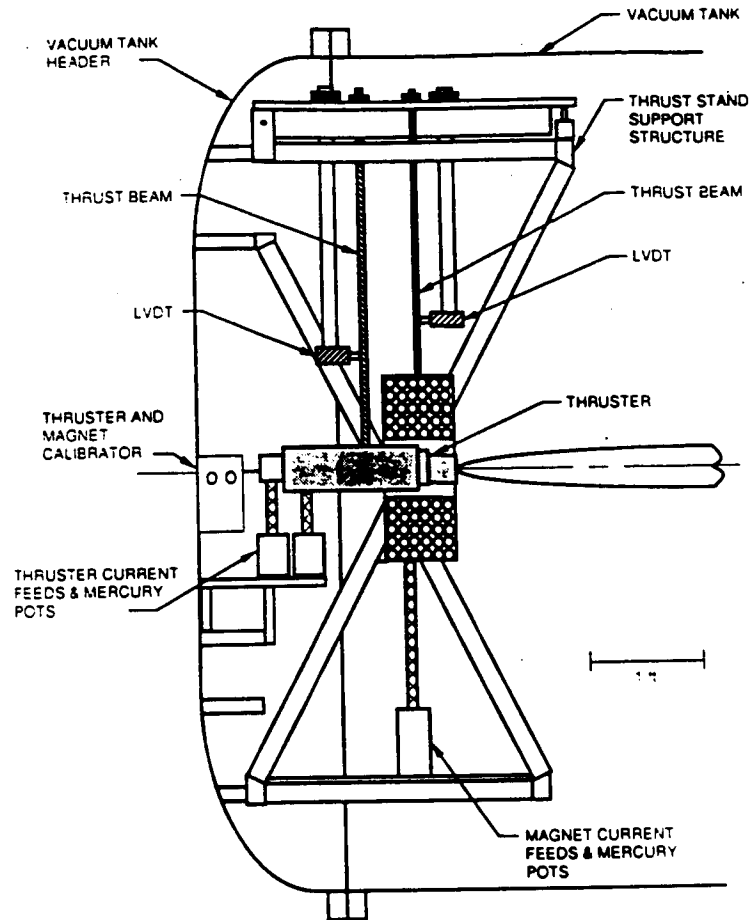
PROGRESS (cont.):

- Preliminary thrust data obtained
- Alternate pumping scheme verified

SUBSEQUENT MILESTONES:

- Demonstrate stable operation over a range of operating conditions at powers ≥ 100 kW
- Develop a database of component thermal data
- Explore approaches to anode thermal management
- Continue development of diffuser to improve backpressure

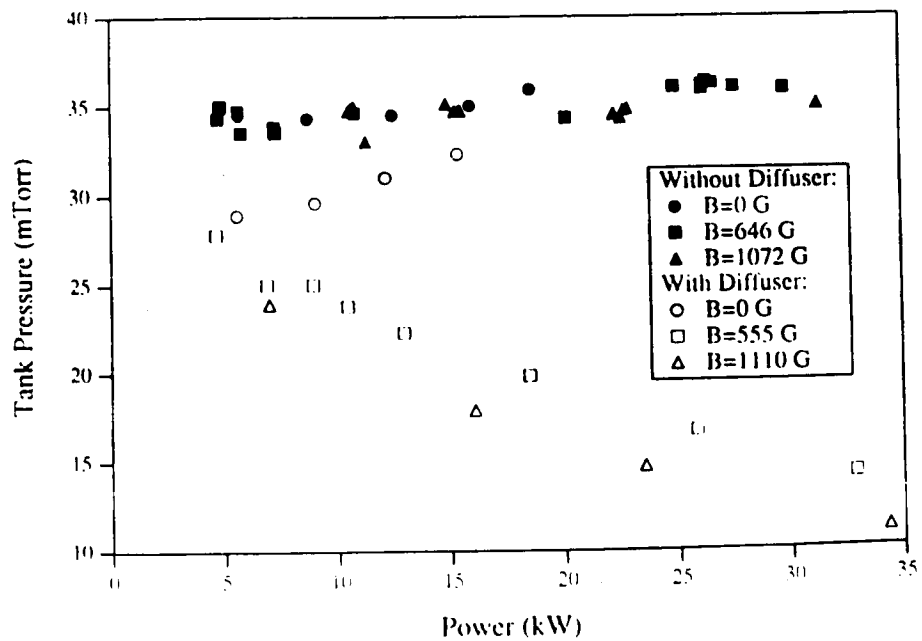
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DIFFUSER EFFECT ON TANK PRESSURE

Mass Flow Rate=0.09 g/s Ar





High-Current Cathode Test Facility

GOAL: Supply thermal data for modelling effort and develop long-lived cathodes for high current applications.

PROGRESS:

- Testing requirements defined
- Vacuum facility obtained



High-Current Cathode Test Facility

PLANNED ACTIVITIES:

- Cathode surface temperature measurements
- Characterization of near-cathode plasma environment
- Erosion measurements and alternate materials evaluation
- Cathode endurance tests



Thruster Component Thermal Modelling

GOAL: Develop capability to predict engine component temperatures for given geometries and operating conditions.

PROGRESS:

- Commercial FEM software procured
- Simple cathode sheath model completed
- Developing cathode thermal model



Thruster Component Thermal Modelling

SUBSEQUENT MILESTONES:

- Complete component thermal models
- Refine electrode sheath models to provide boundary conditions
- Couple component and sheath models with a plasma flow model--potential for JPL-LeRC collaboration
- Experimentally confirm model predictions



Alkali Metal Propellant Studies

GOAL: Evaluate benefits of alkali metal propellants

CURRENT ACTIVITY:

- Performing preliminary assessment of systems-level impact of alkali metal propellants
- Estimating cost of performing alkali metal thruster tests at the JPL Edwards Facility



Alkali Metal Propellant Studies

POTENTIAL FUTURE EMPHASIS:

- Develop facility and expertise in alkali metal handling
- Study effect of propellant on cathode work function
- Verify performance improvements
- Define contamination potential